PL-TR-94-2309

INVESTIGATION OF IONOSPHERIC DISTURBANCES AND ASSOCIATED DIAGNOSTIC TECHNIQUES

L. M. Duncan

Clemson University
E-204 Martin Hall
Clemson, South Carolina 29634-5310

12 December 1994

Final Report
1 January 1992-31 December 1994

Approved for public release; distribution unlimited

PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AFB, MA 01731-3010

"This technical report has been reviewed and is approved for publication"

JOHN QUINN
Contract Manager

EDWARD J. BERGHORN
Branch Chief

WILLIAM K. VICKERY
Division Director

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
12 December 1995

3. REPORT TYPE AND DATES COVERED
Final (1 January 1992-31 December 1994

4. TITLE AND SUBTITLE
Investigation of Ionospheric Disturbances and Associated Diagnostic Techniques

5. FUNDING NUMBERS
PE 62101F
PR 7600 TA 09 WU BI

Contract F19628-90-K-0054

6. AUTHOR(S)
L. M. Duncan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Clemson University
E-204 Martin Hall
Clemson, South Carolina 29634-5310

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Phillips Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010

Contract Manager: John Quinn/GPIA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
PL-TR-94-2309

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
The objectives of this research and development program were to conduct simulation modeling of the generation and propagation of atmospheric acoustic signals associated with surface and sub-surface ground disturbances; to construct an experimental measurement system for exploratory research studies of acoustic-generated ionospheric disturbances; to model high-power radio wave propagation through the ionosphere, including nonlinear wave plasma interaction effects; and to assist in the assessment of diagnostic systems for observation of ionospheric modification experiments using existing and planned high-latitude high-power rf transmitting facilities. A computer simulation of ionospheric response to ground-launched acoustic pulses was constructed and results compared to observational data associated with HF and incoherent scatter radar measurements of ionospheric effects produced by earthquakes and ground-level explosions. These results were then utilized to help define the design, construct and test for an HF Doppler radar system. In addition, an assessment was conducted of ionospheric diagnostic instruments proposed for the Air Force/Navy High-Frequency Active Auroral Research Program (HAARP).

14. SUBJECT TERMS
Atmospheric acoustic signals
Nonlinear wave plasma interactions

15. NUMBER OF PAGES
22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

CONTENTS

1. Electromagnetic Methods for Nuclear Test Monitoring

1.1 *Summary*

Preliminary modeling studies have been conducted to determine the source discrimination applications of joint seismic and electromagnetic observations for underground nuclear test monitoring. The considered source discriminant is based on the ratio of seismic to atmospheric acoustic pulse amplitudes. This is potentially a sensitive parameter in determining the source mechanism. In particular, it is suggested that underground nuclear explosions have a proportionately greater seismic to acoustic pulse ratio than do relatively shallow industrial noise sources such as conventional mining and quarry explosions, and larger more coherent ratio pulse time histories than extended incoherent sources such as small earthquakes.

Remote sensing of the atmospheric acoustic pulse is explored using radio-frequency methods of ionospheric monitoring. Because an atmospheric pulse amplifies as a function of altitude due to decreasing neutral pressure, such ionospheric measurement systems can be extremely sensitive detectors of ground-level acoustic disturbances. Electromagnetic monitoring of the ionosphere has a demonstrated capability to detect and characterize weak acoustic signals from underground and ground-level sources. As the amplified acoustic pulse transits the ionosphere, neutral collisional coupling to the background free electrons, upon which the radio wave propagation depends, transfers the acoustic disturbance into characteristic amplitude and phase disturbances in the electromagnetic signal. The specific measurement method developed here relies upon determining the amplitude and phase of a high-frequency (3-10 MHz) radio wave reflected from the ionosphere in a bistatic transmitter/receiver system. Several frequencies can be monitored simultaneously to provide multiple reflection height diagnostics, and signals transmitted from different transmitter locations can be monitored continuously at each receiver site. The combined system provides an acoustic sensitive network of interconnected radio paths complementing a similar seismic monitoring network.

1.2 *Background.*

It has long been recognized that ground-level explosions generate large atmospheric acoustic disturbances that propagate to ionospheric heights and are subsequently detectable by a number of radio-frequency remote sensing techniques. Indeed, atmospheric nuclear explosions provided large acoustic signal sources that became the experimental standard for early work in this field, with associated acoustic-gravity waves in the upper atmosphere detected around the world (c.e. Hines, 1967). Subsequently, improved measurement instrumentation led to the study of ionospheric disturbances from smaller ground-level chemical explosive sources. Observations of ionospheric response to low-level ground-based sources have become relatively routine, including studies using sources of conventional explosives (Barry et al., 1966; Simons et al., 1981), rocket launches (Duncan and Behnke, 1980); earthquakes (Davies and Baker, 1965; Wolcott et al., 1984), and volcanic eruptions (Roberts et al., 1982). The physics associated with the propagation and detection of these disturbances is relatively well understood.

A number of different observational strategies have been used in the past for detection of larger scale ionospheric disturbances associated with natural and man-made ground-level sources. Principal among these has been chains of vertical ionosondes, initially measuring swept frequency reflection delays as traditional ionograms, and later using discrete frequency phase sounding. Most recent measurement studies have used variations of HF phase sounding.

Modeling and preliminary experimental studies were conducted to determine the source discrimination capabilities of joint seismic and electromagnetic observations for application to nuclear test monitoring. The proposed source discriminant is based upon the hypothesis that the seismic to atmospheric acoustic pulse ratio is a measurable parameter sensitive to the source mechanism. In particular, it is suggested that underground nuclear explosions have a proportionately greater seismic to acoustic pulse ratio than do relatively shallow industrial noise sources such as conventional mining and quarry explosions. Furthermore, it is considered that small earthquakes produce acoustic pulse signatures characteristic of an incoherent line source, associated with their extended fracture zone, rather than the discrete point source of an explosion.

1.3 *Objective*

Seismic measurements at regional distances are acknowledged to be the primary monitoring technology for verification of a low-yield threshold test ban treaty or a comprehensive teat ban. Significant attention has been given to the refinement of methodologies for seismic data acquisition, reduction, and interpretation so as to maximize the associated signal detection and source discrimination capabilities. Similarly, several other geophysical monitoring approaches, with more limited applications as a primary verification technology, are being investigated as complements to seismic measurements. In particular, the present project is the first to explore the theoretical modeling and instrumentation development studies to determine the feasibility of exploiting ionospheric radio observations of atmospheric acoustic disturbances associated with ground-level explosions. These measurements would then be coordinated with regional seismic observations to determine the ration E_A/E_S of amplitudes of the atmospheric acoustic signals. This result can in turn be used to estimate source magnitude, time history, and depth of burial, with subsequent opportunities for enhanced source discrimination. Preliminary results suggest that this approach may significantly reduce source ambiguities for small underground nuclear explosions, near-surface industrial noise such as conventional explosions, and geophysical phenomena such as small earthquakes.

The goals of the present study have been to conduct simulation modeling of the atmospheric acoustic signal generation and propagation process, to determine the required measurement system sensitivity and optimum instrument design and configuration for the proposed ionospheric observations, and to construct a prototype experimental measurement system for exploratory research studies of ionospheric disturbances.

1.4 *Supporting Physics*

The proposed application of ionospheric measurements to nuclear test monitoring requires the computational ability not only to detect the associated acoustic disturbance in the ionosphere, but also to measure its amplitude with sufficient accuracy to reconstruct its approximate original amplitude at the earth's surface. The neutral acoustic wave that traverses the ionosphere as a result of ground motion can be easily calculated for wave amplitudes sufficiently small that wave shock effects can be neglected. In general, the amplification associated with decreasing neutral pressure with height can be calculated based upon the transformation (Pierce and Thomas, 1969) of relative overpressure, $\delta p/p$, as a conservative plane acoustic wave propagates to different altitudes. Then

$$(\delta p/p)_h = (p_o/p_h)^{1/2} \times (\delta p/p)_o \qquad (1)$$

This acoustic amplification factor is shown graphically in Figure 1. Typically this results in an ionospheric signal of the order of 5×10^4 times larger than the intensity of the initial ground-level disturbance. The neutral wave then collisionally couples to free electrons in the height range of 100-400 km, producing a perturbation in the ambient electron density that can be detected by a variety of radio-frequency diagnostic techniques. A number of detection methods can be employed, including high-frequency (HF) bistatic phase sounding; Faraday rotation and dual-frequency dispersion measurements of the integrated electron content; *in situ* measurements; incoherent scatter radar observations; and satellite remote-sensing observations.

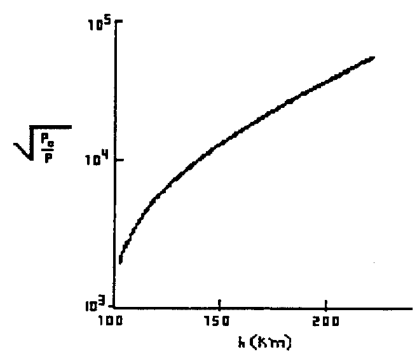

Figure 1. Acoustic amplification factor - relative overpressure versus altitude.

The approach providing the greatest sensitivity for the detection of small acoustic disturbances in the ionosphere is the technique of HF bistatic phase sounding. In this method, a transmitting station radiates weak (< 1 kW) continuous wave (CW) HF signals at several discrete frequencies. At a separate ground station, narrowband HF receivers are tuned to these specific frequencies, monitoring the amplitude and phase of the received signals. The purpose of a bistatic two-station set-up is to eliminate direct ground-wave radiation from the transmitter, which would mask perturbations in the ionospherically reflected signal, and to allow overhead remote-sensing of regions not directly accessible to ground-based instruments. The diagnosed region is approximately at the mid-point of the transmitter-receiver path. Several frequencies are monitored simultaneously to ensure that several ionospheric reflection heights are measured and that observations are maintained through solar terminator, diurnal, and seasonal ionospheric fluctuations. As an estimate of the sensitivity of this technique, we note that relative phase changes can easily be measured to a precision of about 0.01 radian, which at typical HF wavelengths of 50 m corresponds to a sensitivity to height variations in the wave reflection altitude of about 0.1 m. In comparison, explosions of interest for the proposed program are at a level of at least 0.1 kT, producing typical ionospheric disturbances of about 0.1%, or corresponding height fluctuations of about 100 m. Disturbances of this magnitude are routinely detected in association with weak ground-level explosive sources. Indeed, this sensitivity becomes a challenge for distinguishing the explosively-driven acoustic waves in the ionosphere from a background of acoustic fluctuations driven by much smaller or more distant sources such as thunderstorms, supersonic aircraft, and orographic winds. Therefore the problem becomes more one of understanding and interpreting the ionospheric signature of such disturbances, and not one of sensitivity of detection.

We also can compare this technique to other observational alternatives. The fractional pressure excursion $(\delta p/p)_h$ can be estimated for the expected ionospheric detection altitudes and a signal reflection height perturbation of 100 m. The electron density relative perturbation $\delta n/n$ responsible for this height displacement is given by

$$\delta n/n = \delta z/H \tag{2}$$

where the ionospheric scale height H is typically on the order of 25 km, yielding for our example $\delta n/n = 4 \times 10^{-3}$. Using the adiabatic law and allowing for geomagnetic control of plasma motions at ionospheric heights, the neutral gas overpressure can be estimated to be approximately $(\delta p/p)_h = 5 \times 10^{-2}$. Extrapolating back to the ground using the amplification factor described previously, the corresponding source ground-level relative overpressure is estimated to be $(\delta p/p)_o = 10^{-5}$. The corresponding absolute fluctuation level amplitude would be 1 microbar, or about an order of magnitude below typical background levels as measured at ground level by microbarography. We also note that the proposed measurement technique has a systematic measurement sensitivity two to three orders of magnitude greater than the 100 m displacement example used in this comparative analysis.

An acoustic wave launched by a ground-level explosion is a sensitive function of the explosion geometry and surface structures. Near-surface explosions couple more strongly, and retain a broader spectral content. The general shape of the explosion-driven disturbance assumes the form in the ionosphere of a compression wave front followed by a rarefaction. Typical wave refraction spatial scaling is shown in Figure 2. The acoustic wave then appears in the HF phase as an easily distinguishable "N-wave" Doppler signature. A typical observation signature is presented in Figure 3, measured as part of a large HE explosion experiment at White Sands, NM (Simons et al., 1981). To achieve this result, post-processing included signal filtering and noise suppression, and phase detrending to remove natural ionospheric variability acting on much longer time constants.

The measurement and characterization of the acoustic wave in the ionosphere offers reasonable opportunity to accurately characterize the ground-level source function, thereby discriminating near-surface chemical explosions from nuclear explosions at somewhat greater depth and differing spectral composition. Because the ionosphere is subject to acoustic disturbances from many other sources as well, ionospheric monitoring must perform in a relatively noisy operational environment and is not well-suited for independent test detection applications. This independent detection objective has been the approach of several previous investigations of ionospheric monitoring for nuclear test monitoring, with limited success. Instead, the current research is motivated by the potential of ionospheric monitoring to address source discrimination issues as a complement to primary seismic monitoring activities.

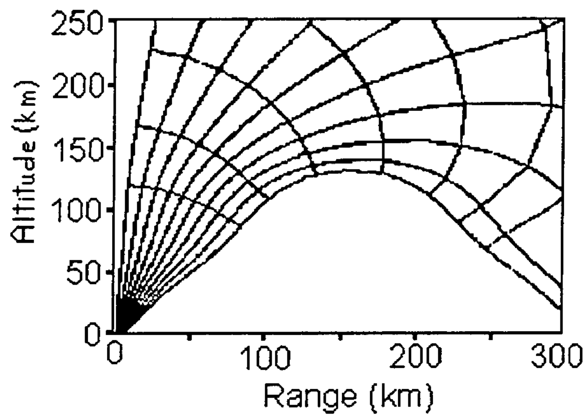

Figure 2. Typical acoustic wave refraction during atmospheric propagation.

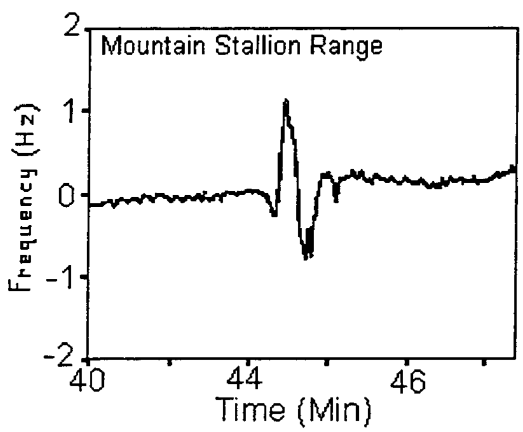

Figure 3. HF Doppler radio acoustic signature of atmospheric disturbance generated by a ground-level explosion.

Coordinated seismic and ionospheric radio acoustic observations are intended to exploit the discriminant relationship of source amplitude, signal time history, and depth of event to assist in distinguishing underground nuclear explosions from other natural and man-made seismic signature sources. Theoretical modeling and computer simulations indicate that the ratio of acoustic to seismic wave amplitudes, E_A/E_S, can be used to help infer source magnitude and temporal characteristics, including depth of burial. In general, atmospheric acoustic signatures are expected to be relatively larger than associated seismic signals for sources at or near the surface, such as industrial explosions, and correspondingly smaller for events at greater depth and less efficient ground-air coupling. Similarly, the time history of the ionospheric radio acoustic disturbance provides additional information on the temporal and spatial coherence of the initial source function, complementing seismic analyses seeking source discriminants based upon signal frequency content. These analyses often must make some hypotheses regarding the source, such as assuming even multiple "ripple fire" detonations in conventional mining explosions. Coordinated ionospheric radio acoustic observations may assist in validating these assumptions.

Computer simulation studies incorporated models of source disturbance, ground-air coupling, acoustic disturbance propagation through the atmosphere, and subsequent radio detection of the free electron manifestation of the neutral acoustic perturbation. All such models are generally a set of basic equations governing the response of the neutral atmosphere, consisting of conservation laws of energy, momentum, mass, and the ideal gas equation of state. Nonlinearities that can be incorporated include advective terms, gravity, gas compressibility, viscosity, and thermal convection. Typically these equations are combined to produce a set of finite difference equations that can then be solved for the expected 1-D, 2-D, or 3-D atmospheric propagation results. Results produced specifically for comparison to seismic source terms (Archambeau et al., 1991) are shown in Figure 4, electron density disturbance at 200 km altitude, and Figure 5, near-surface vertical velocity time series. These results indicate the complexity of the acoustic wave train produced by a realistic topographic source surface and near-surface noise fluctuations. However, in each case the considered discriminant of the initial "N-wave" signature remains intact. The modeling results further quantify the detection thresholds required for the HF bistatic measurement system described in the following section.

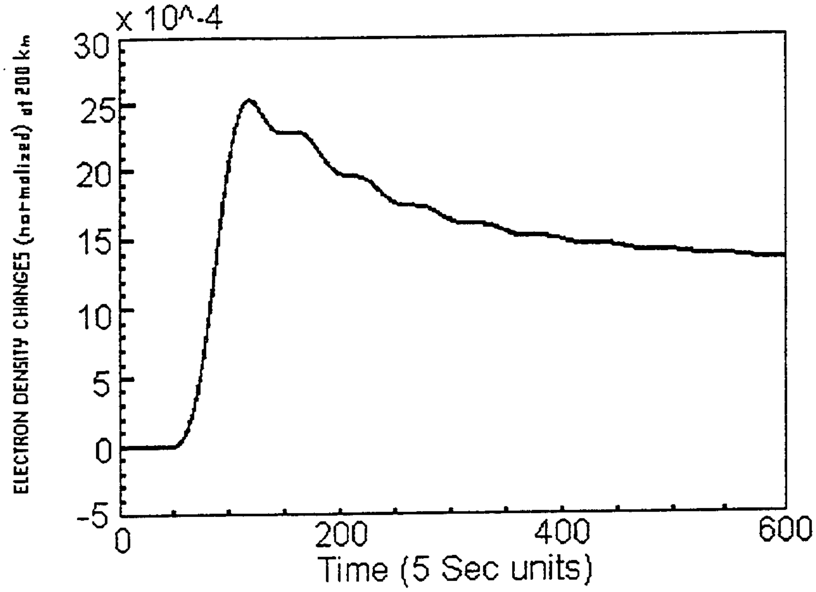

Figure 4. Time Variation of fractional electron density change (Archambeau et al., 1991).

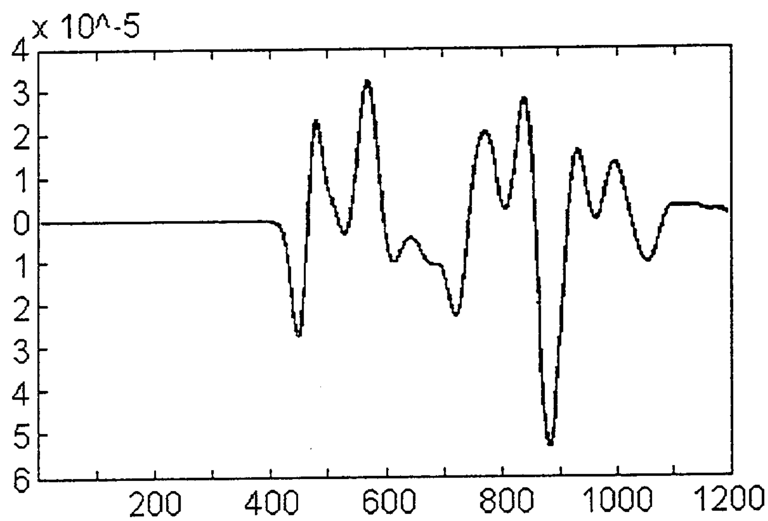

Figure 5. Vertical velocity time series near source region using a layered half space with rough surface topography (Archambeau et al., 1991).

2. Bistatic HF Doppler Radar

The geometrical configuration for operation of a bistatic phase sounder system best utilizes multiple transmitter and receiver sites in an interconnected network. Because expected phase and Doppler frequency variations are of the order of one Hertz, numerous path links can be monitored within a single narrow frequency bandwidth. HF ionospheric sounding systems are most sensitive to acoustic wave effects near the radio wave ionospheric reflection point, which occurs near the transmitter/receiver midpoint. As a result, the ionospheric monitoring equipment sites do not need to be located at the signal source site. Small ground-level explosions have been easily detected on radio paths for transmitter/receiver sites separated by several hundreds of kilometers.

The theoretical modeling analyses and review of past HF ionospheric monitoring have resulted in one significant modification to our original HF Doppler radar design plans. The comparison of acoustic to seismic signals for possible source discrimination applications requires an accurate measurement of the ionospheric acoustic signal amplitude at several different altitudes. Bistatic HF radio signals typically bifurcate in the ionosphere into ordinary and extraordinary polarized wave components with different indices of refraction, and therefore propagating over different paths and reflecting from different heights. The subsequent interference of the reflected signals at essentially the same frequency gives rise to a phenomenon known as polarization fading. Although polarization fading is not a significant limitation to the detection of the "N-wave" signature in received phase typically observed as the ground-launched acoustic disturbance propagates upward through the ionosphere, it does introduce considerable ambiguity in extrapolating back to the initial disturbance amplitude, which is needed for determining the acoustic to seismic source ratio. AS a result of simulation modeling and analysis of previous observational data, we determined a need for an enhanced polarization discrimination specification for receiver performance. Receiver systems initially borrowed from Los Alamos National Laboratory, and dedicated receivers purchased later, were appropriately modified to accommodate this enhanced performance requirement. Testing of various components and operational configurations of the bistatic system were undertaken as part of the WAGS-2 (second Worldwide

Acoustic-Gravity Wave Study) and the coordinated diagnostics campaign at HIPAS (Fairbanks, Alaska) in October, 1992.

We now have completed design and assembly of an HF Doppler radar system suitable for detailed observations of ionospheric acoustic disturbances associated with ground-level sources. This system is capable of transmitting and receiving continuous wave (CW) waveforms at several frequencies over the 2-40 MHz frequency range. A schematic of the constructed system is provided in Figure 6. The transmitting antenna is a simple delta design, launching a broad electromagnetic wave with horizontal linear polarization. The receiving antenna, consisting of two spatially orthogonal dipole antennas, receives the reflected signal components necessary to generate complex returns of left and right circular polarization. These components then correspond to the discrete ordinary and extraordinary components of the ionospheric signal.

The transmitter utilizes a frequency generator signal source to drive a CW signal amplified by a 500 Watt linear amplifier and filtered to remove unwanted harmonics before it is applied to the transmitting antenna terminals.

The return signals received by the spatially distinct receiving dipole antennas are amplified by low-noise amplifiers. These spatial quadrature component signals are then combined in a 90 degree hybrid to provide the left and right circular components of the reflected signal. Modified Racal receivers are used to synchronously demodulate the return signals, providing the in-phase and quadrature components for each polarization. An AT-bus analog-to-digital converter card is used in conjunction with 486-PC computer to convert, process, and store the return signal to a hard disk. Since the time constant of the Doppler signature is large, there is no problem with sample speed and data storage capacity. Furthermore, this large time constant allows the use of narrowband digital filtering to improve the signal detection threshold. The components selected and purchased for the HF Doppler radar system are given in Table 1.

COMPONENT	MODEL	VENDOR
Signal Source	PTS 040M.3T10	Programmed Test Sources
Power Amplifier	BA-100 Linear Amp	Ten-Tech, Inc.
Harmonic Filter	5061 LP Filter	Ten-Tech, Inc.
Low Noise Amplifier	UTO-517	Avantek
Hybrid 90 degree	JH-6-4	Anzak
HF Receiver	R-2174	Racal Communications
A/D Converter	AT-Bus AIO8	Industrial Comp. Source
Signal Processor	33 MHz 486 DX	Gateway 2000

Table 1. Components used for the HF Doppler radar system.

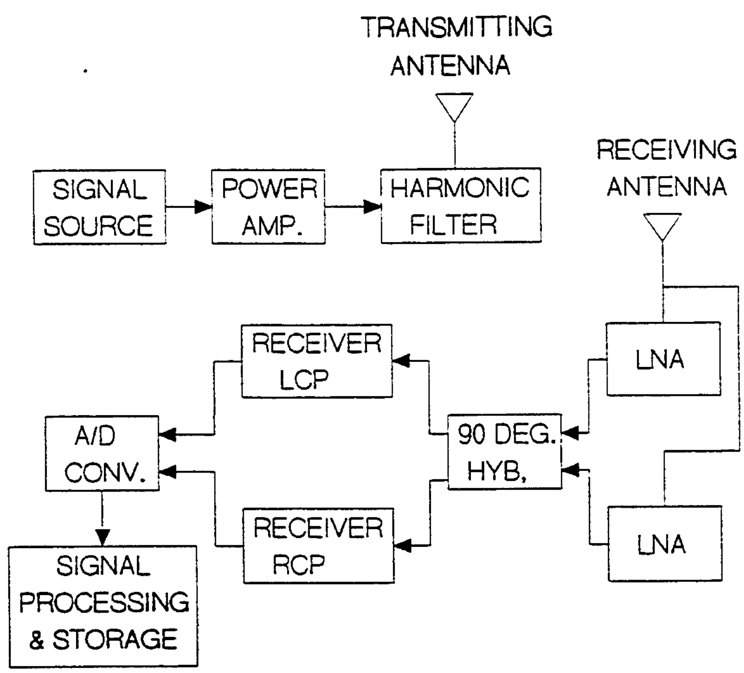

Figure 6. HF Doppler radar system for observing ionospheric acoustic disturbances associated with ground-level explosive sources.

3. High-Power Radio Wave Propagation

A computer model simulating the propagation of a high-power radio wave pulse through the atmosphere and subsequent formation of an artificially ionized layer in the atmosphere by a series of microwave pulses was developed. A modified version of the kinetic theory of the breakdown of air by a powerful microwave emission was incorporated into a model of electromagnetic propagation through the atmosphere by a converging ionizing microwave pulse. This model takes into consideration radio wave self-action as well as absorption, and produces profiles of electron concentration formed in the atmosphere by both an isolated pulse and a series of pulses. Effects of varying the shape of the ionizing pulse are considered, as well as the influence of the ambient electron concentration. Also, the dependence of the electron concentration on the energy and duration of the pulse is investigated. The possible increase in the rate of electron production is considered when using an intense pulse to initiate the breakdown followed by a series of pulses of lesser energy. The influence of the refraction of the microwave beam is estimated. The computer model presented shows that an artificial ionized layer of electrons reaching concentrations of the order of 10^8 cm^{-3} could be formed over a height range of 40-70 km using a reconfigured Arecibo antenna and transmissions at 2.38 GHz with 1-4 MW radiated power. In this application, a pulse compressor would be used to transform CW radiation to electromagnetic pulses with durations of approximately 0.1-0.15 microseconds, with a repetition frequency of 10^3 Hz.

Detailed results of this study are described in a paper under "References."

4. Ionospheric Diagnostics Review

In preparation for the development of an HF Active Auroral Research Program (HAARP) high-power high-frequency ionospheric modification facility, we were also asked to assist in the review of potential diagnostics to be deployed in support of associated ionospheric observations. This review was facilitated through the convening of a "HAARP Science Workshop," held at UCLA 26 - 28 March, 1991, and an "HAARP Workshop on Ionospheric Heating Diagnostics," held at Phillips Laboratory 30 April - 2 May, 1991. Results of this Ionospheric Heating Diagnostics Workshop are published as Air Force Phillips Laboratory report PL/GP Technical Memorandum No. 195. In addition, detailed summaries of HAARP science objectives and proposed diagnostic performance were published in a special issue of Radio Science; see "References."

References

Armstrong, W.T., Argo, P., Carlos, R., Cheung, P.Y., Massey, R., McCarrick, M., Riggin,D., Stanley,J., Wong, A.Y., (1990) "Continuous measurement of stimulated electromagnetic emission spectra from HF excited ionospheric turbulence," Radio Science, **25**:6:1283-1289.

Barry, G.H., Griffiths, L.J., Taenzer, J.C., (1966) "HF radio measurements of high-altitude acoustic waves from a ground-level explosion," J. Geophys. Res. **71**:4173.

Baker, M.R., Collins,T.W., Lee, H.S., Ferraro, A.J., (1990) "A diagnostic system for the study of extremely long wavelength emission produced by ionospheric modification," Radio Science, **25**:6:1369-1373.

Carroll, K.J., Ferraro, A.J., (1990) "Computer simulation of ELF injection into the Earth-ionosphere waveguide," Radio Science, **25**:6:1363-1367.

Close,R.A., Bauer, B.S., Kruer, W. L., Langdon, A. B., Mjolhus, E., Wong, A.Y., (1990) "Computer Simulation of ionospheric radio frequency heating," Radio Science, **25**:6:1341-1349.

Davies, K., Baker, D.M., (1965) "Ionospheric effects observed around the time of the Alaska earthquake of March 28, 1964," J. Geophys. Res. **70**:2251.

Duncan, L.M., behnke, R.A., (1980) "Arecibo observations of ionospheric effects of the HEAO-C Atlas-Centaur rocket launch," in Observations of the HEAO-C Launch Environmental Effects, DOE SPS Report.

Fukuchi, T., Wong,A.Y., Wuerker, R.F., (1990) "Ionospheric RF lidar," Radio Science, **25**:6:1299-1309.

Hines, C.O., (1967) "On the nature of traveling ionospheric disturbances launched by low-altitude nuclear explosions," J. Geophys. Res., **72**:1877.

Katsouleas, T., (1990) "Beat heating of the ionosphere with high power rf pumps," Radio Science, **25**:6: 1359-1362

Kruer, W. L., (1990) "Simulations of electromagnetic wave plasma interactions," Radio Science, **25**:6: 1351-1357.

Lee, H.S., Ferraro, A.J., Olson, J.V., (1990) "Detection and characterization of geomagnetic pulsations using HF ionospheric heating," Radio Science, **25**:6:1429-1483.

Li, P.J., Ferraro, A.J., (1990) "Determination of D region electron densities from the ELF frequency stepping experiment," Radio Science, **25**:6:1387-1395.

McCarrick,M.J., Chouinard,B., Sentman,D.D., Wong, A.Y., Wuerker,R.F., (1990) "Excitation of ELF waves in the Schumann resonance range by modulated HF heating of the polar electrojet," Radio Science, **25**:6:1291-1298.

Mjolhus, E., (1990) "On linear conversion in a magnetized plasma," Radio Science, **25**:6:1321-1339.

Milikh, G.M., Duncan, L.M., Hinds, J.M., (1993) "A computer simulation of the production of an artificially ionized layer using the Arecibo facility," Radio Science, **28**:6:1029-1038.

Olson, J.V., Ferraro, A.J., Lee, H.S., (1990) "Observations of ULF pulsation electric fields in the D region using the high-power auroral simulation heating facility," Radio Science, **25**:6:1423-1427.

Papadopoulos,K., Chang, C.L., Drobot, A., Vitello, P., (1990) "On the efficiency of ionospheric ELF generation," Radio Science, **25**:6:1311-1320.

Roberts, D.H., Klobuchar, J.A., Fougere, P.F., Hendrickson, D.H., (1982) "A large-amplitude traveling ionospheric disturbance produced by the May 18, 1980 explosion of Mount St. Helens," J. Geophys. Res. **87**:6291.

Simons, D.J., Rickel, D.G., Wolcott, J.H., Duncan, L.M., Bernhardt, P.A., Broste,W.B., Albee, P.R., (1981) "The ionospheric response to 600-ton HE experiment at White Sands," EOS Trans, **62**:979.

Wagner, L.S., Goldstein, J.A., Lind, R.W., McCarrick, M.J., Wong, A.Y., (1990) "Channel probe observations of the auroral ionosphere during high-power auroral stimulation heating experiments," Radio Science, **25**:6:1497-1422.

Werner, D.H., Albert, A.M., Ferraro, A.J., (1990) "Implementation of an ELF array of ionospheric dipoles using the high-power auroral simulation facility," Radio Science, **25**:6:1397-1406.

Werner, D.H., Ferraro, A.J., (1990) "Mapping of the polar electrojet current down to ionospheric D region altitudes," Radio Science, **25**:6:1375-1386.

Wolcott, J.H., Simons,D.J., Lee,D.D., Nelson, R.A., (1984) "Observations of an ionospheric pertubation arising from the Coalinga earthquake of May 2, 1983," J. Geophy. Res. **89**:6835.

Wong, A.Y., Brandt, R.G., (1990) "Ionospheric modification - An outdoor laboratory for plasma and atmospheric science," Radio Science **25**:6:1251-1267.

Wong, A.Y., Carroll, J., Dickman, R., Harrison, W., Huhn, W., Lum, B., McCarrick, M., Santoru, J., Schock,C., Wong, G., Wuerker, R.F., (1990) "High-power radiating facility at the HIPAS Observatory," Radio Science **25**:6:1269-1282.